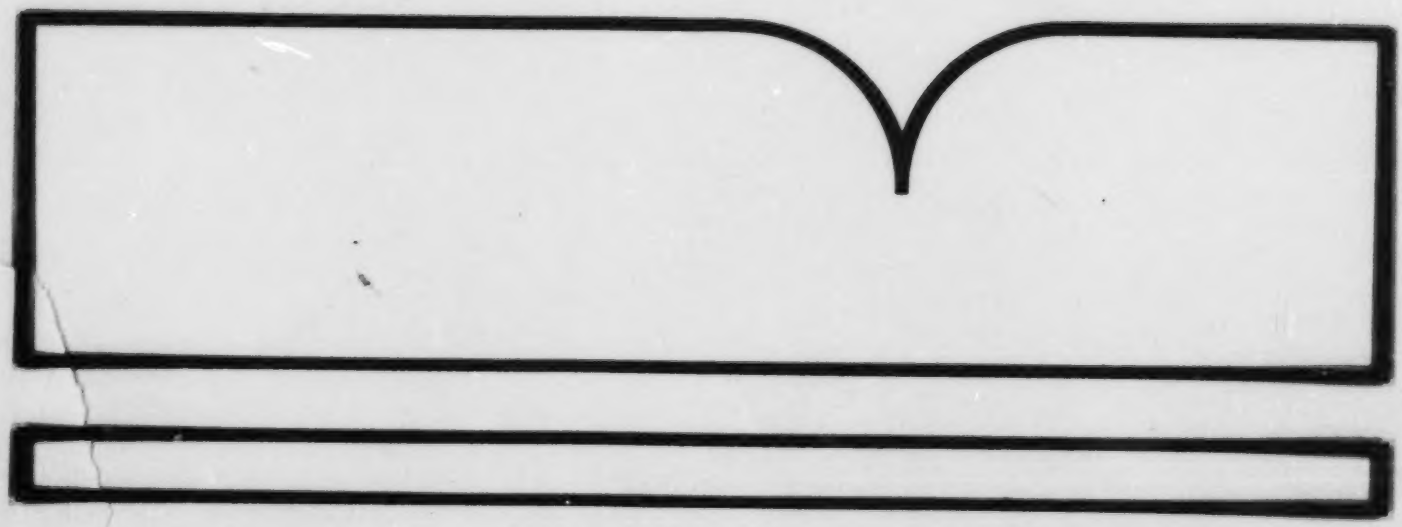
PB84-177484

Metals Removals and Partitioning in Conventional Wastewater Treatment Plants

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

Sep 83



U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO. EPA-600/J-83-191	2.
3. PB84-177484	
4. TITLE AND SUBTITLE Metals Removals and Partitioning in Conventional Wastewater Treatment Plants (Journal Version)	5. REPORT DATE September 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Albert C. Petrasek Jr., and Irwin J. Kugelman	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Municipal Environmental Research Laboratory U. S. Environmental Protection Agency 26 West St. Clair Street Cincinnati, Ohio 45268	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same as Above	13. TYPE OF REPORT AND PERIOD COVERED Journal Article
	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Contact Person: Atal E. Eralp
JWPCF, 55(9):1183-1190, Sept. 1983

16. ABSTRACT

Metals removal and partitioning to primary and secondary sludge during treatment of domestic wastewater by conventional sewage treatment processes was studied. Raw wastewater entering the Mill Creek Sewage Treatment Plant, Cincinnati, Ohio, was fed to a 0.1 l/s (1.6 gpm) pilot treatment plant. The plant consisted of a sewer simulator, aerated grit chamber, primary settler, and activated sludge process. Metals were monitored at the various stages of treatment by analysis of composite samples. Based on mean values, overall removal of As, Ca, Mg, Hg, and SiO_2 was less than 20%; of Ag, Cr and Mn was between 20% and 50% of Cd, Fe, Ni and Zn was between 50% and 80%; and was greater than 80% for Cu and Pb. Average removal for all metals was 42%. The primary sludge contained 10% - 15% of the metals entering the plant while the waste activated sludge contained about 30%. These results are simiar to those recently in other cities of the U.S..

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Metals Partitioning Primary Secondary Sludge		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES 9
	20. SECURITY CLASS (This page)	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

JWPCF, 55(9):1183-1190, Sept. 1983

EPA-600/J-83-191
JOURNAL ARTICLE

© Copyright as part of the September 1983, JOURNAL WATER POLLUTION CONTROL FEDERATION, Washington, D. C. 20037
Printed in U. S. A.

Metals removals and partitioning in conventional wastewater treatment plants

Albert C. Petrasek, Jr., Irwin J. Kugelman

Water used in domestic, commercial, and industrial activities often undergoes significant increases in metals content. Thus, wastewater entering municipal treatment plants frequently has an environmentally significant metals content.[1] The removal and partitioning of metals in treatment plants is important because metals directly impact receiving water quality and suitability of sludges for land application.

EPA's legislated responsibility for controlling discharges of toxicants requires knowledge of the degree to which municipal wastewater treatment plants remove metals, and the extent to which these metals are concentrated in sludge streams. This information is essential for the promulgation of pretreatment regulations, the establishment of publicly owned treatment works (POTW) removal credits for industrial discharges, the establishment of effluent limitations in National Pollutant Discharge Elimination System (NPDES) permits, and for use in mathematical models that can predict the impact of industrial activities on the environment.

To develop additional information on the removal of metals in wastewater treatment plants and the concentration of metals in sludges, EPA's Municipal Environmental Research Laboratory (MERL) conducted a pilot-scale investigation at EPA's Test and Evaluation (T&E) Facility, Cincinnati, Ohio. In this study, the removal and partitioning of metals normally present in wastewater entering the Mill Creek Wastewater Treatment Plant in Cincinnati was determined in a pilot-scale activated sludge system.

PILOT PLANT FACILITIES

The pilot-scale apparatus used was parallel to a sequence of processes designed to evaluate the behavior of organic priority pollutants in conventional wastewater collection and treatment systems.[2,3] The sequence of processes used consisted of a simulated sewer, an aerated grit chamber, a primary clarifier, and a conventional, plug-flow, activated sludge process.

As indicated in Figure 1, raw wastewater from the Cincinnati Metropolitan Sewer District's Mill Creek Wastewater Treatment Plant was pumped to a head tank at the T&E Facility and then routed to the project site. The wastewater was then screened to minimize plugging, and pumped to a flow splitting manifold. The flow then entered a sewer simulator loop consisting of 25.6 m (84 ft) of 102-mm (4-in.) diameter steel pipe on a 7% grade, a 3.15-L/s (50-gpm) recycle pump, and a 380-L (100-gal) sump. The system provided a nominal velocity of 1.5 m/s (4.6 ft/sec) with the pipe half-full and a theoretical residence time of 76 minutes at the design flow of 0.1 L/s (1.6 gpm).

The relative concentration found in waste activated sludge was two to five times greater than that in the primary sludge.

The aerated grit chamber consisted of 0.55-m diameter drums with operating water depths of 0.5 m, which provided theoretical residence times of 20 minutes. Compressed air was supplied to the single diffuser at a rate of 0.1 L/s (0.7 standard cfm).

The primary clarifiers were circular stainless-steel units with 0.91-m diameters and sidewater depths of 1.5 m. The clarifiers had 45° conical bottoms, sludge collectors operating at 5 r/hr, and 0.3-m diameter inlet wells. The design overflow rates and residence times were 12.4 m^3/m^2 and 3.2 hours, respectively.

The aeration basins were five-pass rectangular, stainless-steel units with 0.61-m widths, 3.05-m lengths, and 1.37-m sidewater depth (SWD). The geometry resulted in theoretical residence times of 7.5 hours, based on the design flow of 0.1 L/s. The secondary clarifiers were identical to the primary clarifiers.

SAMPLING AND ANALYTICAL PROCEDURES

Twenty-four-hour composite samples were collected for all process flows and sludges throughout the duration

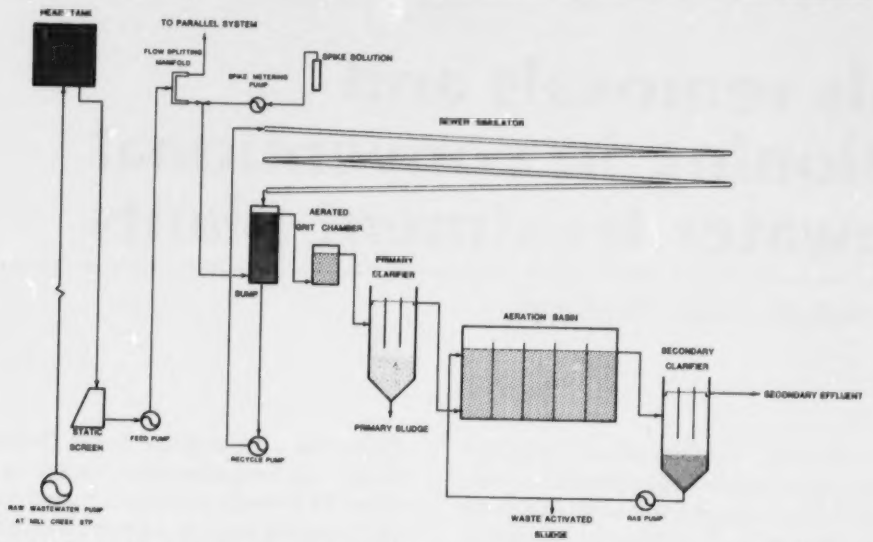


Figure 1—Simplified process schematic diagram of the spiked treatment sequence.
the spiked treatment sequence.

of this project. The influent, primary clarifier effluent, activated sludge effluent, mixed liquor, and return activated sludge were composited from six grab samples taken at 4-hour intervals. The primary sludge was composited from three grab samples collected at 8-hour intervals. The 24-hour composites were analyzed for conventional water quality parameters such as chemical oxygen demand (COD), total organic carbon (TOC), ammonia nitrogen (NH_3-N), and total Kjeldahl nitrogen (TKN).

Two sets of weekly composite samples were prepared from the 24-hour composite samples. One set was acidified with 2 mL of HNO_3 per litre. The other set of weekly composite samples was not acidified. All samples were stored at 4°C. The unacidified samples were used for total dissolved solids (TDS), SiO_2, SO_4, F, Cl, Mg, and Ca determinations. The acidified samples were used for Ag, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn analyses.

Additionally, appropriate grab samples were collected at 4-hour intervals for routine process control testing that included mixed liquor and return sludge respiration rates, effluent turbidities, settled sludge volumes (30 minutes), pH, and alkalinity.

Metals determinations were performed after nitric acid digestion in an autoclave at 121°C for 15 minutes by atomic absorption (AA) spectrophotometry, using, in most cases, direct aspiration.[4] Low concentrations were determined by using appropriate furnace procedures.[4] The basic AA for all determinations was equipped with automatic aspiration, and was interfaced with a laboratory management and analytical quality control computer system.[5] The computer automatically generated calibration curves and final sample concentrations and performed quality control functions by monitoring for precision and accuracy.

PILOT PLANT OPERATION

Table 1 presents a summary of the process operation for the 312-day study period. The influent flow averaged 0.083 L/s and had a mean variation of only 6.1%. The return activated sludge (RAS) flow averaged 0.035 L/s, or 42% of the influent flow for the system. The mixed liquor suspended solids (MLSS) and RAS concentrations were approximately 1 900 mg/L and 6 400 mg/L, respectively.

The system was operated at a nominal solids residence time (SRT) of 7 days, which resulted in a food to microbe (F/M) ratio of 0.6 kg COD applied per day kg MLSS, or a F/M of 0.18 on a TOC basis. The normalized oxygen uptake rates (OUR) for the mixed liquor and RAS were 0.041 and 0.018 mg/L·h, respectively.

Median water quality data for the treatment sequence

Table 1—Summary of process operation.

Influent flow, Q, L/s (gpm)	0.083 (1.31)
RAS flow, Qr; L/s (gpm)	0.035 (0.55)
Waste activated sludge, L/d (gpd)	169 (44.7)
Waste primary sludge, L/d (gpd)	34 (9.1)
Waste primary sludge, mg/L	32 700
MLSS, mg/L	1 887
RAS concentration, mg/L	6 382
Normalized ML-OUR, hr^{-1}	0.041
Normalized RAS-OUR, hr^{-1}	0.018
SVI, mL/gm	111
SRT, days	6.7
F/M (COD), $days^{-1}$	0.61
F/M (TOC), $days^{-1}$	0.19

Table 2—Median water quality values for the treatment sequence.

Parameter	Influent (mg/L)	Primary clarifier effluent (mg/L)	Activated sludge effluent (mg/L)	Overall removal (%)
TSS	490	265	26	95
COD	650	390	74	89
TOC	180	122	18	90
T-P	8.3	5.6	2.9	65
NH_3-N	20	19	1.5	93
NO_2 and NO_3-N	.1	.1	3.6	—
Alkalinity (as $CaCO_3$)	—	300	188	—
Turbidity (NTU)	—	—	21	—

are summarized in Table 2. These data indicate that the pilot-scale system provided good treatment. Total suspended solids (TSS), COD, and TOC reductions were 95, 89, and 90%, respectively.

The primary clarifier performed well during the study, effecting a 46% reduction in TSS and a 45% decrease in COD concentrations. The primary sludge flows averaged 0.5% of the influent flow, and primary sludge concentrations ranged from 1.5 to 8% by weight, and averaged 3.3%.

The performance of the activated sludge process was generally very satisfactory during the project, with median secondary effluent TSS and COD concentrations reaching 26 mg/L and 74 mg/L, respectively. The activated sludge process reduced total phosphorus concentrations by 48%, down from 5.6 to 2.9 mg/L. A 92% reduction in ammonia nitrogen occurred in the activated sludge process, producing a median NH_3-N concentration of 1.5 mg/L in the secondary effluent.

REMOVAL OF METALS FROM WASTEWATERS

The wastewater entering the Mill Creek Wastewater Treatment Plant has a significant industrial contribution, and, thus, several of the pollutants are present in relatively high concentrations.[1]

Table 3 presents comparative data on mean influent metals concentrations observed in Washington, D.C.;[6] Dallas, Tex.;[7] Cincinnati, Ohio; the maximum and minimum concentrations reported in a study of 20 POTWs,[8] and two data sets from a survey of 239 wastewater treatment plants.[9] Data from the 239-plant survey are grouped by facilities receiving less than 4% industrial flow and those receiving 4% or more industrial flow. For all thirteen metals reported, concentrations observed at Cincinnati were higher than those reported for either the District of Columbia or Dallas. In many instances (Zn, Pb, Mn, Cu, Cr), the differences exceeded one order of magnitude. However, the means reported for Cincinnati were all lower than the maximums reported in the 20-plant study, although the mean Pb and Cu concentrations are very close. With the exceptions of silver and mercury, all metals studied were found in significant concentrations in the influent to the Mill Creek plant. By comparison, the D.C. data are representative of a wastewater with only a minor industrial contribution. The Dallas data reflect a substantial industrial input (17% by flow), but of a significantly different nature than that found in Cincinnati.

The data from the 239-plant survey indicate substantial increases in metals concentrations as a result of industrial discharges. The Cincinnati data have higher mean concentrations than the means of the plants re-

Table 3—Comparison of metals concentrations in raw wastewater observed in four studies.

Metal	Wash., DC (mg/L)	Dallas, Tex. (mg/L)	Cincinnati, Ohio (mg/L)	20-City survey Min. (mg/L)	20-City survey Max. (mg/L)	239-Plant survey industrial flow <4% (mg/L)	239-Plant survey industrial flow >4% (mg/L)
Ag[a]	3.98	0.78	8.0	2.0	77.0	3.0	18.8
As[a]	1.49	14.8	20.6	2.0	80.0	2.5	135.5
Ca	—	54.6	86.0	—	—	—	—
Cd[a]	1.2	14.0	20.9	1.0	1 800	9.5	16.6
Cr	0.017	0.205	0.63	0.008	2.38	0.025	0.145
Cu	0.049	0.224	0.80	0.034	1.19	0.095	0.151
Fe	1.3	1.07	4.29	—	—	1.52	2.16
Hg[a]	0.8	0.43	<2.0	0.20	3.90	0.6	1.2
Mg	—	0.86	17.6	—	—	—	—
Mn	0.015	0.018	0.65	—	—	0.148	0.124
Ni	—	0.062	0.45	0.011	1.93	0.037	0.140
Pb	0.023	0.052	0.88	0.016	0.935	0.042	0.103
Zn	0.11	0.366	1.24	0.023	7.68	0.238	0.354

[a] μg/L.

ceiving industrial flow reported in the 239-plant survey, two exceptions being silver and arsenic.

The mean metals concentrations observed in the influent, primary effluent, and activated sludge effluent are presented in Table 4, along with percent removals computed from the mean concentrations. Additionally, metals removals were computed for each sample set and frequency distributions of the percent removals were developed. The frequency distributions of the observed metals removals are presented in Table 5. It is important that significant differences often exist in metals removal data when the removals are computed from mean concentrations, median concentrations, or median removals based on frequency distribution data. More pronounced differences in removal data, computed from means, medians, and frequency distributions, will generally occur as the data base becomes more skewed.

The data in Table 4 show that the influent concentrations for both silver and mercury were quite low, 8.0 and 2.0 μg/L, respectively. Good estimates of removability cannot be made from the data. Based on mean concentrations, copper, iron, and lead removals were all greater than 75%. When evaluated for median removals, five metals (Cd, Cr, Cu, Fe, and Pb) had removals greater than 75%. For these metals, the greatest removals occurred in the activated sludge process.

Arsenic removal was not particularly good. Only 19% were removed, based on mean concentrations. As expected, both calcium and magnesium were quite refractory, with no substantial removals obtained.

Zinc removals were 63%, based on mean concentrations, and 69%, based on median removals. Total plant removals for nickel were 60 and 40%, based on mean concentrations and median removals, respectively. Manganese was relatively refractory, with removals of 39% (means) and 33% (median removals).

PARTITIONING TO SLUDGES

Partitioning of metals to particulate materials and the subsequent concentrations in the sludge streams is widely known.[10–12] Table 6 presents the observed metals concentrations in both the waste activated sludge and the primary sludge. Concentrations are reported as mg/L and mg/kg of dry solids. Additionally, concentration factors for the metals studied are reported for both of the sludges. The concentration factors were computed by dividing the mean metal concentrations in the appropriate sludges by the mean influent concentrations.

The concentrations of the metals (mg/L basis) observed in the waste activated sludge are typically lower than the concentrations in the primary sludge. The reported concentration factors are correspondingly lower in the waste activated sludge. However, an entirely different situation exists when the concentrations are evaluated for mg of metals per kg of dry solids. The concentrations in the waste activated sludge are much higher than those for the primary sludge. With respect to the toxic metals, concentrations greater than 2 000 mg/kg were observed for Cr, Cu, Pb, and Zn in the waste activated sludge. Additionally, Ca, Fe, and Mg were present in the waste activated sludge at 16 609, 6 678, and 3 761 mg/kg, respectively.

The general tendency for the metals to partition to

Table 4—Mean metals concentrations and removals observed during this study.

Parameter	Influent (mg/L)	Primary clarifier effluent (mg/L)	Primary clarifier removal (%)	Activated sludge effluent (mg/L)	Activated sludge removal (%)	Total plant removal (%)
Ag[a]	8.0	9.0	0	<5.0	44	38
As[a]	20.6	16.0	16	16.7	0	19
Ca	86.0	81.0	6	81.0	0	6
Cd[a]	20.9	17.0	19	7.9	54	62
Cr	0.63	0.51	19	0.34	33	46
Cu	0.80	0.57	29	0.16	72	80
Fe	4.29	2.44	43	1.01	59	77
Hg[a]	<2.0	<2.0	0	<2.0	0	0
Mg	17.6	18.0	0	17.9	1	0
Mn	0.65	0.55	15	0.4	27	39
Ni	0.45	0.27	40	0.18	33	60
Pb	0.88	0.58	34	0.11	81	88
Zn	1.24	1.28	0	0.46	64	63
Cl	269	277	0	291	0	0
F	0.6	0.7	0	0.7	0	0
SO_4	288	279	3	289	0	0
SiO_2	45.1	46.7	0	40.0	14	11
TDS	1537	1446	6	1389	4	10

[a] μg/L.

Table 5—Frequency distributions for observed metals removals.

Metal	Treatment sequence	Percent of time metal removal greater than or equal to indicated value					
		5	10	25	50	75	90
		Observed removals					
Ag	Secondary	75	64	49	21	<10	<10
	Primary	83	74	47	<10	<10	<10
As	Secondary	82	70	<10	<10	<10	<10
	Primary	82	68	<10	<10	<10	<10
Cd	Secondary	96	95	88	75	62	34
	Primary	75	71	52	29	<10	<10
Cr	Secondary	92	91	85	78	55	15
	Primary	80	67	47	24	<10	<10
Cu	Secondary	95	93	89	85	61	49
	Primary	71	64	52	39	14	<10
Fe	Secondary	92	91	90	86	69	37
	Primary	81	76	61	41	14	11
Mn	Secondary	67	60	46	33	20	<10
	Primary	54	49	36	18	<10	<10
Ni	Secondary	88	79	60	40	<10	<10
	Primary	72	62	46	17	<10	<10
Pb	Secondary	97	96	95	92	83	14
	Primary	89	80	64	42	<10	<10
Zn	Secondary	85	82	80	69	57	12
	Primary	77	71	47	24	<10	<10

the activated sludge is apparent in the mass balances presented in Table 7. The relative percentages of metals found in the waste activated sludges was usually two to five times greater than the amount present in the primary sludges.

DISCUSSION

Several investigators have reported the concentration dependence of metals removal data,[7,13] which imply that higher influent concentrations result in greater metals removals. During this study, silver, mercury, and arsenic were present at very low concentrations in the raw wastewater. Therefore, proper assessment of removability was not possible for these metals. The concentrations of the other 10 metals were sufficient to permit removability and mass balance calculations with reasonable accuracy.

The arsenic removal (mean concentrations) observed for this study was 19%, which is in good agreement with removals of 9 and 19% reported for two studies conducted at Dallas, Tex.[7,14] However, As data are probably not indicative of the metal's behavior in a treatment plant because of analytical variability at low concentrations.

Calcium and magnesium are quite refractory to the biological processes, and essentially no removal of these metals by conventional treatment processes has been reported by other investigators.[15,16] These findings were verified by this study.

Manganese removal for the total treatment sequence averaged only 39%, with the primary clarifier removing 15% and the activated sludge process removing 27%. These data are in good agreement with other research, which reported 37% manganese removal in a municipal treatment plant.[17]

Comparative removal data from four additional sources are presented for seven of the metals studied in Table 8. The research reported by Oliver and Cosgrove[17] was a 4-week study of metals removals in a conventional primary and activated sludge secondary treatment plant receiving domestic and industrial wastewaters. The data from Dallas represent removals by the activated sludge process only. The metals study was approximately 2.5

Table 6—Summary of observed metals concentration factors in sludges.

Metal	Influent (mg/L)	Waste activated sludge			Primary sludge		
		(mg/L)	(mg/kg)	Concentration factor	(mg/L)	(mg/kg)	Concentration factor
Ag	0.008	0.12	18.8	14.6	0.18	5.47	22.4
As	0.021	0.16	25.1	[illegible]	0.114	3.49	5.5
Ca	86.0	106	16 609	1.2	524	16 024	6.1
Cd	0.021	0.088	13.8	4.2	0.139	4.25	6.7
Cr	0.63	15.8	2 474	25.1	20.4	625	32.4
Cu	0.80	18.0	2 817	22.5	31.0	948	38.8
Fe	4.29	42.6	6 678	9.9	51.5	1 574	12.0
Hg	<0.002	—	<1.4	—	0.018	<0.55	>9.0
Mg	17.6	24.0	3 761	1.4	64.3	1 966	3.7
Mn	0.65	10.7	1 669	16.5	20.5	628	31.5
Ni	0.45	4.5	699	10.0	14.6	445	32.4
Pb	0.88	15.1	2 368	17.2	32.2	985	36.6
Zn	1.24	19.0	2 977	15.3	46.4	1 417	37.4

Table 7—Summary of mass balance calculations.

Parameter	Percent of influent in		Mass balance primary clarifier	Percent of influent in		Mass balance total system
	Primary effluent	Primary sludge		A.S. effluent	Waste A.S.	
Ag	112.3	10.7	123.0	61.1	34.6	106.4
As	97.3	0.3	97.6	78.4	17.9	96.5
Ca	93.7	2.9	96.6	91.5	0.0	94.4
Cd	80.7	3.1	83.9	36.7	9.9	49.8
Cr	80.6	15.4	96.0	52.5	59.1	126.9
Cu	70.9	18.4	89.3	19.4	53.0	90.8
Fe	56.6	5.7	62.3	22.9	23.4	52.0
Hg	<100.0	<0.4	<100.4	<99.5	<10.9	100.8
Mg	101.8	1.7	103.5	98.8	3.2	103.8
Mn	84.2	15.0	99.2	59.8	38.6	113.4
Ni	59.8	15.3	76.1	38.8	23.3	77.4
Pb	65.6	17.4	83.0	12.2	40.5	70.1
Zn	102.7	17.7	120.5	36.0	36.1	89.9
Cl	102.5	0.6	103.1	105.1	2.5	108.2
F	116.9	0.1	117.0	113.4	2.0	115.5
SO_4	96.8	0.1	96.9	97.5	0.3	98.0
SiO_2	103.1	0.7	103.8	86.2	11.0	97.9
TDS	93.6	0.8	94.4	87.8	4.4	92.9

years long. The reuse study was conducted for 6 months.[7,14] The guidelines data were taken from summaries presented by the EPA in "Federal Guidelines—State and Local Pretreatment Programs."[13] The Cincinnati data are from this research.

Rather good agreement is apparent for the reported metals removals. The data in Table 8 for Zn are relatively consistent. Also, Stones has reported Zn removals of 57%.[18] Two additional studies of Zn report removals of 90 and 85%.[19,20]

Mercury was present in concentrations too low to assess removability in this study, and in the two Dallas studies. However, Ghosh and Zugger[21] have reported Hg removals ranging from 51 to 58%.

Table 8—Comparison of metals removals observed in five different studies.

Metal	Oliver & Cosgrove	Dallas[b] metals study	Dallas[a] reuse study	Guidelines[c]	Cincinnati[a] study
Cd	80	49	58	10	62
Cr	79	65	65	52	46
Cu	73	68	74	69	80
Hg	>85	[d]	[d]	49	[d]
Ni	16	25	[d]	9	60
Pb	93	54	53	46	88
Zn	77	62	44	71	63

[a] Acidified weekly composite samples.
[b] Acidified daily composite samples.
[c] For secondary plants, from Table 6-5, reference 11.
[d] Observed concentrations too low to evaluate removability.

The removals for Cd and Ni in the guidelines appear to be low when compared to the other data. However, the reported nickel data are quite variable. Removals observed during this study were 60% by means and 33% by medians. McDermott *et al.*, have reported Ni removals ranging from 28 to 42%.[22] Barth *et al.*, reported 31% Ni removal in a system with an influent concentration of 1.6 mg/L.[20] Stones has reported 27.3% Ni removal in activated sludge.[23]

The lead removals observed during this study, and by Oliver and Cosgrove, are considerably higher than the other three studies shown in Table 8. Stones has reported 92% Pb removal by the activated sludge process.[24]

The reported copper removals are consistent. Additionally, McDermott *et al.*, reported Cu removals ranging from 75 to 79%,[25] and Barth *et al.* reported 54% Cu removal.[20]

CONCLUSIONS

The ability of municipal wastewater treatment plants to remove metals is an important consideration for both environmental protection and water resources management. Additionally, the extent to which metals are concentrated in sludges can directly effect the selection of solids handling processes and the ultimate disposal process.

This research, and the other studies, provide a fairly comprehensive data base for metals removals in conventional wastewater treatment plants using primary settling and activated sludge processes. However, one must anticipate that the fixed-film processes and lagoons

will perform differently. Additionally, improved metals removals may be observed at influent metals concentrations higher than those encountered during this study.

The metals concentrations observed in the primary sludge were generally higher than in the return activated sludge when considered in units of mg/L. However, on a mg/kg basis, the waste activated sludge had higher concentrations.

The primary sludge contained 10 to 15% of the metals entering the plants. The waste activated sludge contained about 30% of the total metals burden. The average removal of the 13 metals studied was 42%, based on the mass balance calculations.

Metals removals were computed by using both mean concentrations and median removals obtained from frequency distributions. For those metals with large standard deviations in the influent samples, substantial differences in the removal efficiencies were apparent. For those metals with better behaved data, both calculations yielded approximately the same removal. Because of the variability of metals concentrations usually observed, careful considerations should be given to the use of mean, median, or modal concentrations for the computation of removal efficiencies, and to the development of percent removal frequency distributions.

Several areas of importance were beyond the scope of this particular study. The partitioning of metals between the soluble and insoluble fractions, and the inhibitory effects of metals on the activated sludge process, both require additional research. Studies in these two areas are currently being conducted.

The authors hope the data presented in this paper will be a valuable resource for federal, state, and local agencies in the development of industrial wastewater pretreatment regulations, and that the data will aid industry in its environmental management and control technology decision-making processes. The information should also prove useful to those directly involved in facilities design and operation because it permits evaluation of the effect of metals partitioning to the sludges on various ultimate disposal options.

ACKNOWLEDGMENTS

Authors. Albert C. Petrasek is chief of the MERL Pilot Projects Test and Evaluation Facility, U.S. EPA, Municipal Environmental Research Laboratory in Cincinnati Ohio. Irwin J. Kugelman is now director of the Center for Marine and Environmental Studies, Lehigh University, Bethlehem, Pa. At the time of this research, Kugelman was chief of the Pilot and Field Evaluation Section, Municipal Environmental Research Laboratory, U.S. EPA, Cincinnati, Ohio. Correspondence should be addressed to Albert C. Petrasek, Jr., MERL Pilot Projects, Text and Evaluation Facility, U.S. EPA, Municipal Environmental Research Lab., Cincinnati, OH 45268.

REFERENCES

1. Petrasek, A. C., "Behavior of Selected Toxic Substances in Wastewater Collection and Treatment Systems." Paper presented at Conference on Combined Municipal/Industrial Wastewater Treatment, Richardson, Tex. (Mar. 1980).
2. Petrasek, A. C., *et al.*, "Behavior of selected organic compounds in wastewater collection and treatment systems." Paper presented at WPCF 53rd Annual Conference, Las Vegas, Nev. (Sept. 1980).
3. Petrasek, A. C., *et al.*, "Fate of toxic organic compounds in wastewater treatment plants." Accepted for publication in *J. Water Pollut. Control Fed.* (Dec. 1982).
4. "Methods of Chemical Analysis of Water and Wastes, Section 200." EPA-600/4-79-020, Environ. Monit. and Support Lab., Cincinnati, Ohio (March 1979).
5. Almich, B. P., "SFC: The New EPA Laboratory Data Management and Analytical Quality Control Computer System." Paper presented at the 15th Annual Meeting of the U.S. Public Health Service Prof. Assoc. (May 1980).
6. Warner, H. P., and English, J. N., "Wastewater Treatment for Reuse and Its Contribution to Water Supplies." U.S. EPA Rep. No. EPA-600/2-78-027), Munic. Environ. Res. Lab., Cincinnati, Ohio (March 1978).
7. Esmond, S. E., *et al.*, "The Removal of Metals and Viruses in Advanced Wastewater Treatment Sequences." U.S. EPA Rep. No. EPA-600/2-80-149, Munic. Environ. Res. Lab., Cincinnati, Ohio (Aug. 1980).
8. Feiler, H.,"Fate of Priority Pollutants in Publicly Owned Treatment Works, Intern Report." U.S. EPA Rep. No. EPA-440/180-301, Off. of Water Reg. and Stand., Washington, D.C. (Jan. 1980).
9. Minear, R. A., *et al.*, "Data Base for Influent Heavy Metals in Publicly Owned Treatment Works." Draft Final Rep., Grant No. R805606-01. Project Officer, S. A. Hannah, Munic. Environ. Res. Lab., U.S. EPA, Cincinnati, Ohio (1981).
10. Neufeld, R. D., and Hermann, E. R., "Heavy metal removal by acclimated activated sludge." *J. Water Pollut. Control Fed.*, **47**, 310 (1975).
11. Cheng, M. H., *et al.*, "Heavy metal uptake by activated sludge." *J. Water Pollut. Control Fed.*, **47**, 2 (1975).
12. Nelson, P. O., *et al.*, "Factors Affecting the Fate of Heavy Metals in the Activated Sludge Process." *J. Water Pollut. Control Fed.*, **53**, 1323 (1981).
13. "Federal Guidelines State and Local Pretreatment Programs, Volume II, Appendices 1-7." Constr. Grants Program Inf. Rep. No. EPA-430/9-76-0176, U.S. EPA, Washington, D.C. (Jan. 1977).
14. Petrasek, A. C., "Wastewater Characterization and Process Reliability for Portable Wastewater Reclamation." U.S. EPA Rep. No. EPA-600/2-77-210, Munic. Environ. Res. Lab., Cincinnati, Ohio (Nov. 1977).
15. "A 'State-of-the-Art' Review of Health Aspects of Wastewater Reclamation for Groundwater Recharge." State

Water Resour. Control Board, Dep. of Water Resour., Dep. of Health, State of Calif., Sacramento (Nov. 1975).
16. "Evaluation of Industrial Cooling Systems Using Reclaimed Municipal Wastewater, Applications for Potential Users." Rep. of the Off. of Water Recycling, Calif. State Water Resour. Control Board, Sacramento, Calif. (Nov. 1980).
17. Oliver, B. G., and Cosgrove, E. G. "The Efficiency of Heavy Metal Removal by a Conventional Activated Sludge Treatment Plant." *Water Res.*, **8**, 869 (1974).
18. Stones, T., "The Fate of Zinc During the Treatment of Sewage." *J. Inst. Sew. Purif.*, **2**, 254 (1959).
19. McDermott, G. N., *et al.*, "Zinc in Relation to Activated Sludge and Anaerobic Digestion Processes." Proc. 17th Ind. Waste Conf., Lafayette, Indiana, May 1–3, 1962. Eng. Ext. Ser. 112 Eng. Bull., Purdue Univ., **47**, 2 (March 1963).
20. Barth, E. F., *et al.*, "Effects of a Mixture of Heavy Metals on Sewage Treatment Processes." Proc. 18th Ind. Waste Conf., Lafayette, Indiana, April 30-May 2, 1963. Engr. Ext. Ser. 115, Eng. Bull., Purdue Univ., **48**, 3 (May 1964).
21. Ghosh, M. M., and Zugger, P. D., "Toxic Effects of Mercury on the Activated Sludge Process." *J. Water Pollut. Control Fed.*, **45**, 424 (1973).
22. McDermott, G. N., *et al.*, "Copper and Anaerobic Sludge Digestion." **35**, 655 (May 1963).
23. Stones, T., "The Fate of Nickel During the Treatment of Sewage." *J. Inst. Sew. Purif.*, **82**, 252 (1959).
24. Stones, T., "The Fate of Lead During the Treatment of Sewage." *J. Inst. Sew. Purif.*, 221 (1960).
25. McDermott, G. N., "Effects of Copper on Aerobic Biological Sewage Treatment." *J. Water. Pollut. Control. Fed.*, **35**, 227 (1963).